

**APPARATUS FOR FORMING THIN FILMS AND  
METHODS FOR FORMING CAPACITORS ON  
SEMICONDUCTOR SUBSTRATES USING SAME**

Related Application

This application is related to Korean Application No. 99-39839, filed September 16, 1999, the disclosure of which is hereby incorporated herein by reference.

Field of the Invention

The present invention relates to apparatus and methods for forming films on substrates, and more particularly, to apparatus having multiple-chambers for forming thin films on semiconductor substrates and methods of using such apparatus to form capacitors on semiconductor substrates.

Background of the Invention

As the device density on semiconductor substrates increases resulting in highly integrated semiconductor devices, it may be desirable to increase capacitance in a restricted cell area. Various methods have been proposed, for example, decreasing the thickness of the dielectric layer, increasing the effective surface areas of electrodes, and/or using dielectric layers having large dielectric constants such as ferroelectric materials. As used herein, dielectric layers having large dielectric constants including ferroelectric films are referred to as high dielectric layers.

5 A ferroelectric material such as  $\text{PbZrTiO}_3$  (PZT) or  $\text{BaSrTiO}_3$  (BST) may be used as the high dielectric layer. Unlike a silicon oxide layer, a silicon nitride layer, or a tantalum oxide layer, the ferroelectric material may exhibit a spontaneous polarization phenomenon. The ferroelectric material also typically has a dielectric constant between several hundreds and several thousands. Therefore, since the equivalent oxide thickness of the high dielectric layer is equal to or less than  $10\text{\AA}$  even though the high dielectric layer is formed to a thickness of  $500\text{\AA}$ , it may be possible to significantly increase capacitance when the high dielectric layer is used for a capacitor.

10 When a capacitor of a highly integrated semiconductor device is formed, the high dielectric layer such as BST or PZT preferably has a high dielectric constant and an excellent step coverage. The resulting capacitor preferably has an excellent leakage current characteristic. To achieve this, a metal organic chemical vapor deposition (MOCVD) method is typically used to form the high dielectric layer.

15 However, when the high dielectric layer such as the BST layer formed by the MOCVD method is applied to the capacitor, the high dielectric layer is typically formed at a high temperature of more than about  $500^\circ\text{C}$  in order to improve the leakage current characteristic of the capacitor. While the leakage current characteristic of the resulting capacitor may be good, the step coverage of a high dielectric layer formed at the high temperature may be less than about 50%, which is generally considered to be poor. When the step coverage of the high dielectric layer is poor, the high dielectric layer may not be suitable for use in a highly integrated semiconductor device, which has a distance between storage electrodes (the lower electrodes of the capacitor) that is relatively narrow. Also, when the high dielectric layer is formed at the high temperature of more than about  $500^\circ\text{C}$ , a barrier metal layer may be oxidized.

25  
30 To solve the above problems, the high dielectric layer may be deposited at a low temperature of less than about  $500^\circ\text{C}$  where the step

coverage of the high dielectric layer is good. However, when the high dielectric layer is deposited at the low temperature, post-annealing may be required because the high dielectric layer is deposited as an amorphous layer having a dielectric constant of less than about 50. Additionally, the leakage current characteristic of the capacitor may deteriorate since impurities may remain in the dielectric layer. These impurities may be, for example, a carbon component generated from an organic metal source that is used as the raw material of the high dielectric layer.

In order to remove the impurities which may remain in the high dielectric layer, a method of crystallization annealing the high dielectric layer at a high temperature of greater than about 600°C may be provided after depositing the high dielectric layer at the low temperature of less than about 500°C. However, when the high dielectric layer is crystallization annealed at the high temperature of greater than about 600°C, the electrode of the semiconductor device capacitor and the barrier metal layer may be oxidized and the high dielectric layer may deteriorate. Also, the remaining impurities may not be removed even though the high dielectric layer deposited at the low temperature of less than about 500°C is crystallization annealed at the high temperature of more than about 600°C.

### Summary of the Invention

According to embodiments of the present invention, methods and apparatus for oxygen radical annealing or plasma annealing various layers (e.g., a lower electrode, a dielectric layer, or an upper electrode) of a microelectronic capacitor on a substrate are provided. By oxygen radical or plasma annealing the lower electrode of the capacitor, the leakage current characteristic of the capacitor may be improved such that the leakage current is reduced, for example, by a factor of 100 or more. The amount of impurities on the lower electrode may also be reduced. Oxygen radical or plasma annealing the dielectric layer of the capacitor may

improve the leakage current characteristics of the capacitor and may reduce the amount of impurities in the dielectric layer. By oxygen radical annealing the upper electrode, the leakage current characteristic of the capacitor may be improved and the number of oxygen vacancies formed in the dielectric layer may be reduced.

In a first aspect, embodiments of the present invention provide an apparatus for forming a thin film on a substrate having a multi-functional chamber for depositing a dielectric layer on the substrate and an oxygen radical or plasma annealing unit connected to the multi-functional chamber. The oxygen radical or plasma annealing unit provides oxygen radical or plasma gas to the multi-functional chamber to oxygen radical or plasma anneal one or more electrodes and/or dielectric layers on the substrate in the multi-functional chamber.

In other embodiments of the present invention, the oxygen radical or plasma annealing unit is an ozone generator or a plasma generator. The plasma generator is capable of generating a plasma gas selected from the group consisting of  $O_2$ ,  $NH_3$ , Ar,  $N_2$ , and  $N_2O$ . The multi-functional chamber includes an ozone or plasma gas remover connected to an exhaust end of the multi-functional chamber.

In still other embodiments of the present invention, the multi-functional chamber includes a support plate configured to hold the substrate, a heater unit positioned under the support plate, a source dispersion device positioned above the support plate configured to uniformly disperse organic source liquid, and a source supplier in fluid communication with the source dispersion device. The source supplier includes a liquid mass flow controller configured to control a flow of organic source liquid, an evaporator in fluid communication with the flow controller configured to evaporate the source liquid, and a transfer gas source in fluid communication with the evaporator configured to transfer an organic source from the evaporator to the source dispersion device. The source supplier includes between 1 and 3 evaporators.

In yet other embodiments of the present invention, the apparatus includes a cleaning gas supplier in fluid communication with the multi-functional chamber configured to supply cleaning gas to remove dielectric material from a wall of the multi-functional chamber. The apparatus  
5 includes a transfer chamber configured to transfer the substrate from a first chamber to a second chamber. The multi-functional chamber is connected to the transfer chamber. The apparatus includes a loadlock chamber configured to introduce the substrate into the apparatus. The loadlock chamber is connected to the transfer chamber. The apparatus includes an  
10 electrode deposition chamber, a crystallization annealing chamber, an oxygen radical or plasma annealing chamber configured to pre-treat a lower electrode, and/or a cooling chamber and a pre-heating chamber, each of which is connected to the transfer chamber.

In another aspect, embodiments of the present invention provide an  
15 apparatus for forming a thin film on a substrate having a crystallization annealing chamber for processing a substrate, and an oxygen radical or plasma annealing unit connected to the crystallization annealing chamber. The oxygen radical or plasma annealing unit provides oxygen radical or plasma gas to the crystallization annealing chamber to oxygen radical or  
20 plasma anneal an electrode or dielectric layer on the substrate in the crystallization annealing chamber.

In other embodiments of the present invention, the apparatus includes a transfer chamber configured to transfer the substrate from a first chamber to a second chamber. The crystallization chamber is connected  
25 to the transfer chamber. The apparatus includes a loadlock chamber configured to introduce the substrate into the apparatus, a dielectric layer deposition chamber, and/or an electrode deposition chamber, each of which is connected to the transfer chamber.

In still another aspect, embodiments of the present invention provide  
30 an apparatus for forming a thin film on a substrate having an oxygen radical or plasma annealing chamber configured to post-treat a dielectric

layer and/or an upper electrode, and an oxygen radical or plasma annealing unit connected to the oxygen radical or plasma annealing chamber. The oxygen radical or plasma annealing unit provides oxygen radical or plasma gas to the oxygen radical or plasma annealing chamber to oxygen radical or plasma anneal a dielectric layer and/or an upper electrode on the substrate in the oxygen radical or plasma annealing chamber.

In other embodiments of the present invention, the apparatus includes a transfer chamber configured to transfer the substrate from a first chamber to a second chamber. The oxygen radical or plasma annealing chamber configured to post-treat a dielectric layer and/or an upper electrode is connected to the transfer chamber. The apparatus includes a loadlock chamber for introducing the substrate to the apparatus, a dielectric layer deposition chamber, and/or an electrode deposition chamber, each of which is connected to the transfer chamber. The apparatus includes an oxygen radical or plasma annealing chamber configured to pre-treat a lower electrode, a crystallization annealing chamber, and/or a cooling chamber and a pre-heating chamber, each of which is connected to the transfer chamber.

Embodiments of the present invention also provide methods for forming a capacitor on a substrate including the operations of forming a lower electrode on a substrate, forming a dielectric layer on the lower electrode, oxygen radical or plasma annealing the dielectric layer, and forming an upper electrode on the oxygen radical or plasma annealed dielectric layer.

In other embodiments of the present invention, the operations of forming a dielectric layer and oxygen radical or plasma annealing the dielectric layer are performed in the same chamber. The oxygen radical annealing of the dielectric layer includes the operation of exposing the dielectric layer to an atmosphere including an oxygen radical, which may be ozone, and maintaining the temperature of the dielectric layer equal to

or less than 500°C during the exposing operation. The plasma annealing of the dielectric layer includes the operation of exposing the dielectric layer to an atmosphere comprising a plasma gas, such as O<sub>2</sub>, NH<sub>3</sub>, Ar, N<sub>2</sub>, and N<sub>2</sub>O, and maintaining the temperature of the dielectric layer equal to or less than 500°C during the exposing operation. The operations of forming and oxygen radical or plasma annealing the dielectric layer may be performed repeatedly. The dielectric layer may be various dielectric materials, such as Ta<sub>2</sub>O<sub>5</sub>, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, Y<sub>2</sub>O<sub>3</sub>, SrTiO<sub>3</sub>, BaTiO<sub>3</sub>, SrTiO<sub>3</sub>, PbZrTiO<sub>3</sub>, SrBi<sub>2</sub>Ta<sub>2</sub>O<sub>9</sub>, PbZrO<sub>3</sub>, LaZrO<sub>3</sub>, PbTiO<sub>3</sub>, LaTiO<sub>3</sub>, and Bi<sub>4</sub>Ti<sub>3</sub>O<sub>12</sub>.

In still other embodiments of the present invention, the methods include the operation of oxygen radical or plasma annealing the lower electrode. Oxygen radical or plasma annealing the lower electrode, depositing the dielectric layer, and oxygen radical or plasma annealing the dielectric layer are performed in the same chamber. Oxygen radical or plasma annealing the lower electrode, forming the dielectric layer, oxygen radical or plasma annealing the dielectric layer, and forming the upper electrode are performed in-situ by one apparatus for forming a thin film.

In yet other embodiments, the methods include the crystallization annealing of the dielectric layer after forming the upper electrode. The operations of oxygen radical or plasma annealing the lower electrode, forming the dielectric layer, oxygen radical or plasma annealing the dielectric layer, forming the upper electrode, and crystallization annealing the dielectric layer are performed in-situ by one apparatus for forming a thin film.

In other embodiments of the present invention, the methods include the operation of crystallization annealing the dielectric layer after oxygen radical or plasma annealing the dielectric layer. The oxygen radical or plasma annealing of the dielectric layer and the crystallization annealing of the dielectric layer are performed in the same chamber. The operations of forming the dielectric layer, oxygen radical or plasma annealing the dielectric layer, crystallization annealing the dielectric layer, and forming

the upper electrode are performed in-situ by one apparatus for forming a thin film.

In another aspect, embodiments of the present invention provide methods for forming a capacitor on a substrate including the operations of forming a lower electrode on a substrate, forming a dielectric layer on the lower electrode, forming a first upper electrode on the dielectric layer, and oxygen radical annealing the upper electrode.

In other embodiments of the present invention, the oxygen radical annealing operation includes the operations of exposing the upper electrode to an atmosphere containing ozone, and maintaining the temperature of the upper electrode at equal to or less than 500°C during the exposing operation. The methods include forming a second upper electrode on the oxygen radical annealed first upper electrode.

As described above, apparatus and methods according to the present invention may form capacitors having improved current leakage characteristics. Impurities and defects in one or more layers of the capacitors may also be reduced while maintaining the improved current leakage characteristics.

#### Brief Description of the Drawings

Figure 1 is a graph illustrating a comparison of the leakage current of a capacitor having a high dielectric layer ozone annealed according to embodiments of the present invention versus the leakage current of a capacitor formed without such ozone annealing;

Figure 2 is a graph illustrating a comparison of the leakage current of a capacitor having a high dielectric layer plasma annealed according to embodiments of the present invention versus the leakage current of a capacitor formed without such plasma annealing;

Figure 3 is a graph illustrating a comparison of the distribution of remaining carbon impurities in a high dielectric layer ozone annealed



according to embodiments of the present invention versus the level of such impurities in a high dielectric layer that was not ozone annealed;

Figure 4 is a graph illustrating a comparison of the leakage current of a capacitor having a lower electrode ozone annealed according to  
5       embodiments of the present invention versus the leakage current of a capacitor formed without such ozone annealing;

Figure 5 is a graph illustrating a comparison of the leakage current of a capacitor having an upper electrode deposited in an oxygen atmosphere according to embodiments of the present invention versus the  
10       leakage current formed without such deposition;

Figure 6 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention having a multi-functional chamber in fluid communication with an oxygen radical or plasma annealing unit;

Figure 7 is a schematic diagram illustrating embodiments of the multi-functional chamber shown in Figure 6 and having an ozone generator as an oxygen radical annealing unit;

Figure 8 is a schematic diagram illustrating embodiments of the multi-functional chamber shown in Figure 6 and having a plasma generator as a plasma annealing unit;

Figure 9 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention similar to the embodiments of Figure 6 and having an electrode deposition chamber;

Figure 10 is a schematic diagram illustrating embodiments of the electrode deposition chamber shown in Figure 9;

Figure 11 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention similar to the embodiments of Figure 9 and having a crystallization annealing  
30       chamber;

Figure 12 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention having a dielectric layer deposition chamber in fluid communication with an oxygen radical or plasma annealing unit and an electrode deposition chamber;

Figure 13 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention similar to the embodiments of Figure 12 and having a crystallization annealing chamber;

Figure 14 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention similar to the embodiments of Figure 12 and having an oxygen radical or plasma annealing chamber configured to pre-treat a lower electrode;

Figure 15 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention having a dielectric layer deposition chamber, an electrode deposition chamber, and a crystallization annealing chamber in fluid communication with an oxygen radical or plasma annealing unit;

Figure 16 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention similar to the embodiments of Figure 13 and having a cooling chamber;

Figure 17 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention having a dielectric layer deposition chamber, an electrode deposition chamber, and an oxygen radical or plasma annealing chamber configured to post-treat a dielectric layer and/or an upper electrode in fluid communication with an oxygen radical or plasma annealing unit;

Figure 18 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention similar to the embodiments of Figure 17 and having an oxygen radical or plasma annealing chamber configured to pre-treat a lower electrode;

Figure 19 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention similar to the embodiments of Figure 17 and having a crystallization annealing chamber;

5           Figure 20 is a schematic diagram illustrating embodiments of an apparatus for forming a thin film according to the present invention similar to the embodiments of Figure 19 and an oxygen radical or plasma annealing chamber configured to pre-treat a lower electrode, a pre-heating chamber, and a cooling chamber;

10           Figure 21 is a flow diagram illustrating embodiments of a method for manufacturing a capacitor on a substrate according to the present invention where the steps of oxygen radical or plasma annealing a lower electrode, depositing a dielectric layer, and oxygen radical or plasma annealing the dielectric layer are performed in one chamber, and where  
15           the aforementioned steps and the step of depositing an upper electrode are performed in-situ;

            Figure 22 is a flow diagram illustrating embodiments of a method for manufacturing a capacitor on a substrate according to the present invention similar to the embodiments of Figure 21 and performing  
20           crystallization annealing in-situ;

            Figure 23 is a flow diagram illustrating embodiments of a method for manufacturing a capacitor on a substrate according to the present invention similar to the embodiments of Figure 21 and without performing crystallization annealing;

25           Figure 24 is a flow diagram illustrating embodiments of a method for manufacturing a capacitor on a substrate according to the present invention where the steps of oxygen radical or plasma annealing a dielectric layer and performing crystallization annealing are performed in a multi-functional chamber, and where the aforementioned steps and the  
30           steps of oxygen radical or plasma annealing a lower electrode, depositing a dielectric layer, and depositing an upper electrode are performed in-situ;

Figure 25 is a flow diagram illustrating embodiments of a method for manufacturing a capacitor on a substrate according to the present invention similar to the embodiments of Figure 24 except the lower electrode is not oxygen radical or plasma annealed;

5           Figure 26 is a flow diagram illustrating embodiments of a method for manufacturing a capacitor on a substrate according to the present invention similar to the embodiments of Figure 22 except the lower electrode is not oxygen radical or plasma annealed and the substrate is pre-heated prior to dielectric deposition and cooled after crystallization  
10           annealing;

          Figure 27 is a flow diagram illustrating embodiments of a method for manufacturing a capacitor on a substrate according to the present invention similar to the embodiments of Figure 22 where a lower electrode is formed in situ;

15           Figure 28 is a flow diagram illustrating embodiments of a method for manufacturing a capacitor on a substrate according to the present invention similar to the embodiments of Figure 23 except the lower electrode is not oxygen radical or plasma annealed and the upper electrode is oxygen radical annealed;

20           Figure 29 is a flow diagram illustrating embodiments of a method for manufacturing a capacitor on a substrate according to the present invention similar to the embodiments of Figure 28 where a second upper electrode is formed on the oxygen radical annealed first upper electrode;

          Figure 30 is a lateral cross-section of a capacitor formed on a  
25           substrate using the embodiments of Figure 28.

#### Description of Preferred Embodiments

          The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred  
30           embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited

to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. In the drawings, the thickness of layers and regions are exaggerated for clarity.

5 Like numbers refer to like elements throughout. It will be understood that when an element such as a layer, region or substrate is referred to as being "on" another element, it can be directly on the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly on" another element, there are no intervening  
10 elements present. As used herein, "in situ" means performing various processes without exposing the workpiece to an environment that may contaminate it, such as air.

According to embodiments of the present invention, it is now possible to manufacture thin films and capacitors on substrates, preferably  
15 semiconductor substrates, such that the thin films have lower impurity levels and the capacitors have improved electrical characteristics (e.g., an improved leakage current characteristic). As used herein, capacitors are devices having a lower electrode on the substrate, a dielectric layer on the lower electrode, and an upper electrode on the dielectric layer. The  
20 dielectric layer is preferably a high dielectric layer, such as  $Ta_2O_5$ ,  $Al_2O_3$ ,  $TiO_2$ ,  $Y_2O_3$ ,  $SrTiO_3$  (STO),  $BaTiO_3$ ,  $SrTiO_3$ ,  $PbZrTiO_3$  (PZT),  $SrBi_2Ta_2O_9$  (SBT),  $PbZrO_3$ ,  $LaZrO_3$ ,  $PbTiO_3$ ,  $LaTiO_3$ , and  $Bi_4Ti_3O_{12}$ . Hereinafter, a BST layer having a perovskite structure is used as an example of the high dielectric layer.

25 Apparatus and methods of embodiments of the present invention may reduce the amount of impurities such as carbon and carbon dioxide, which may remain on the lower electrode or in the dielectric layer when the lower electrode is oxygen radical or plasma annealed or the high dielectric layer is oxygen radical annealed, respectively. Also, oxygen radical  
30 annealing the upper electrode may limit the formation of oxygen vacancies in the high dielectric layer. The leakage current of the capacitor may be

reduced by oxygen radical or plasma annealing the lower electrode,  
oxygen radical or plasma annealing the dielectric layer, or oxygen radical  
annealing the upper electrode. In addition to apparatus and methods for  
oxygen radical or plasma annealing thin films, embodiments of the present  
invention provide an apparatus for forming a thin film that may limit the  
absorption of impurities onto or into the workpiece by performing a plurality  
of operations, such as forming a lower electrode, oxygen radical or plasma  
annealing the lower electrode, forming a dielectric layer, oxygen radical or  
plasma annealing the dielectric layer, forming an upper layer, and/or  
oxygen radical annealing the upper layer, in situ.

In detail, referring now to Figure 1, a graph illustrates a comparison  
of the leakage current of a capacitor having a high dielectric layer ozone  
annealed according to embodiments of the present invention versus the  
leakage current of a capacitor formed without such ozone annealing.  
Figure 1 shows the leakage current characteristic of the capacitor having  
the following structure: a Pt layer (a lower electrode)/a BST layer (a high  
dielectric layer)/a Pt layer (an upper electrode). The BST layer was formed  
in an amorphous state to a thickness of 150Å on the lower electrode Pt  
layer, which was at 420°C. In Figure 1, reference characters **a** and **b**  
denote a case where the BST layer is ozone annealed and a case where  
the BST layer is not ozone annealed, respectively.

As shown in Figure 1, performing the ozone annealing operation  
allows a larger voltage to be applied to the capacitor for a given leakage  
current value. Thus, the leakage current at desirable voltages is lower (i.e.,  
the leakage current characteristic of the capacitor is improved) when the  
ozone annealing is performed than when the ozone annealing is not  
performed. The improved leakage current characteristics may be due to a  
decrease in the level of impurities in the BST layer when the ozone  
annealing is performed after forming the high dielectric layer.

Referring now to Figure 2, a graph illustrates a comparison of the  
leakage current of a capacitor having a high dielectric layer plasma

annealed according to embodiments of the present invention versus the leakage current of a capacitor formed without such plasma annealing. Figure 2 shows the leakage current characteristic of the capacitor having the following structure: a Pt layer (a lower electrode)/a BST layer (a high dielectric layer)/a Pt layer (an upper electrode). The BST layer was be  
5 formed in an amorphous state to a thickness of 220Å on the lower electrode Pt layer, which was at 420°C. In Figure 2, reference characters **a** and **b** denote a case where the plasma annealing is performed in a N<sub>2</sub>O plasma gas atmosphere after forming the BST layer and a case where the plasma annealing is not performed, respectively.  
10

As shown in Figure 2, performing the plasma annealing operation allows a larger voltage to be applied to the capacitor for a given leakage current value. Thus, the leakage current at desirable voltages is lower (i.e., the leakage current characteristic of the capacitor is improved) when the plasma annealing is performed than when the plasma annealing is not  
15 performed. The improved leakage current characteristics may be due to a decrease in the level of impurities in the BST layer when the plasma annealing is performed after forming the high dielectric layer.

In Figure 3, a graph illustrates a comparison of the distribution of remaining carbon impurities in a high dielectric layer ozone annealed according to embodiments of the present invention versus the level of such impurities in a high dielectric layer that was not ozone annealed. Impurities such as carbon may remain in the BST layer deposited in an amorphous state at a low temperature equal to or less than 500°C. **Table 1** shows  
20 how carbon impurities are distributed for various annealing conditions. Carbon distribution was measured using a time of flight-secondary ion mass spectroscopy (TOF-SIMS) of a BST layer having a thickness of 150Å in the amorphous state.  
25

Table 1

Sample	Deposition thickness and temperature of BST layer	Annealing conditions after depositing BST layer
a	150Å/420°C	Not annealed
b	150Å/420°C	N <sub>2</sub> +O <sub>2</sub> (5%) annealed at 650°C for 30 minutes
c	150Å/420°C	Ozone annealed at 350°C
d	150Å/420°C	Ozone annealed at 350°C and N <sub>2</sub> +O <sub>2</sub> (5%) annealed at 650°C for 30 minutes

As shown in Figure 3, the amount of carbon detected from the ozone annealed samples **c** and **d** is smaller than the amounts of carbon detected from other non-ozone annealed samples. As less carbon remains in the ozone annealed dielectric layer, the leakage current characteristic of capacitors formed with such layers may be improved.

The leakage current may be reduced by decreasing the impurities such as CO<sub>2</sub> and C absorbed into the lower electrode because the leakage current of the capacitor of the semiconductor device constituted of the lower electrode/the high dielectric layer/the upper electrode may be suppressed by the shottky barrier generated by the difference between the work function of the electrode and the work function of the high dielectric layer.

Referring now to Figure 4, a graph illustrates a comparison of the leakage current of a capacitor having a lower electrode ozone annealed according to embodiments of the present invention versus the leakage current of a capacitor formed without such ozone annealing. Figure 4 shows the leakage current characteristic of the capacitor having the following structure: a Ru layer (a lower electrode)/a BST layer (a high dielectric layer)/a Ru layer (an upper electrode). In Figure 4, reference characters **a** and **b** denote a case where the lower electrode is ozone



annealed and a case where the lower electrode is not ozone annealed, respectively. The lower electrode is ozone annealed at a temperature of 350°C with gas having an ozone density of 10% for 5 minutes.

As shown in Figure 4, the leakage current is  $1 \times 10^{-5}$  A/cm<sup>2</sup> at 1.0 V when the lower electrode is oxygen radical annealed by ozone according to embodiments of the present invention, and the leakage current is  $5 \times 10^{-3}$  A/cm<sup>2</sup> at 1.0 V when the lower electrode is not oxygen radical annealed by ozone. Thus, by use of embodiments of the present invention, the leakage current may be reduced, for example, by a factor of about 100. This improvement in leakage current characteristic may be caused by a reduction in the level of impurities on the oxygen radical annealed lower electrode.

Referring now to Figure 5, a graph illustrates a comparison of the leakage current of a capacitor having an upper electrode deposited in an oxygen atmosphere according to embodiments of the present invention versus the leakage current formed without such deposition. When thermal treatment for crystallization is performed and the upper electrode is formed at the same time in a reducing atmosphere at high temperature, for example in an N<sub>2</sub> atmosphere at a temperature equal to or more than 650°C, the leakage current of the resulting capacitor may increase because oxygen vacancies may be easily formed in the BST layer, allowing the Pt of the upper electrode to migrate. According to embodiments of the present invention, oxygen is added during the formation of the upper electrode, which may improve the electrical characteristics of the capacitor.

Figure 5 shows the leakage current characteristic of a capacitor having the following structure: a Pt layer (the lower electrode)/a BST layer (the high dielectric layer)/a Pt layer (the upper electrode). Reference characters **a** and **b** denote a case where oxygen is added when the upper electrode is deposited in the reducing atmosphere, i.e., N<sub>2</sub> atmosphere at a

temperature of 650°C, for the crystallization of the BST layer and a case where oxygen is not added, respectively.

As shown in Figure 5, when oxygen is not added, the leakage current is  $5 \times 10^{-3}$  A/cm<sup>2</sup> at 1.0 V. However, when oxygen is added, the leakage current is  $2 \times 10^{-6}$  A/cm<sup>2</sup> at 1.0 V. Accordingly, the addition of oxygen according to embodiments of the present invention may reduce the leakage current by, for example, a factor of 1,000. The leakage current may be reduced when oxygen is added during the deposition of the upper electrode because the Pt of the upper electrode becomes PtO. Thus, oxygen contained in the upper electrode may prevent the formation of oxygen vacancies in the BST layer and the migration of Pt of the upper electrode during N<sub>2</sub> thermal treatment.

According to embodiments of the present invention, it may be possible to form a PtO upper electrode more easily and to strongly combine the upper electrode with the high dielectric layer when the upper electrode is deposited and is oxygen radical annealed than when oxygen is added during the formation of the upper electrode. In particular, when the upper electrode is deposited as a thin film and annealed by oxygen radical, it may be possible to lower the temperature at which the BST layer is crystallized and to improve the characteristic of an interface between the BST layer and the upper electrode. When the upper electrode is annealed in the reducing atmosphere, it may be possible to prevent the migration of Pt from the upper electrode.

Referring now to Figure 6, embodiments of an apparatus for forming a thin film according to the present invention having a multi-functional chamber in fluid communication with an annealing unit will now be described. While apparatus of embodiments of the present invention may form various thin films, it is preferable that they form the thin films of capacitors on highly integrated semiconductor substrates. These thin films may include the lower electrodes, dielectric layers, and upper electrodes of capacitors on semiconductor substrates. The apparatus includes a

loadlock chamber **5** having a cassette **3** loaded with one or more semiconductor wafers **1** (a semiconductor substrate). The loadlock chamber **5** is connected to a transfer chamber **9**. The transfer chamber **9** may be used to transfer the semiconductor wafer **1** from a first chamber within the apparatus to a second chamber within the apparatus. While the transfer chamber **9** as illustrated in Figure 6 has robot arms **7** for loading and unloading the semiconductor wafer **1**, it is to be understood that various means for loading and unloading the semiconductor wafer **1** may be used.

As shown in Figure 6, the transfer chamber **9** is connected to a multi-functional chamber **11**, which is connected to an oxygen radical or plasma annealing unit **13**. The oxygen radical or plasma annealing unit **13** may be an oxygen radical generator (e.g., an ozone generator) or a plasma generator. The multi-functional chamber **11** can oxygen radical or plasma anneal a lower electrode, oxygen radical or plasma anneal a high dielectric layer, or oxygen radical anneal an upper electrode using oxygen radicals or plasma provided by the oxygen radical or plasma annealing unit **13**. The multi-functional chamber can also deposit the dielectric layer. By performing multiple operations in the multi-functional chamber **11**, it may be possible to reduce the time required for loading and unloading the semiconductor wafer, pre-heating and cooling the semiconductor wafer, and moving the semiconductor wafers to individual chambers. Accordingly, apparatus of embodiments of the present invention may reduce some of the expenses incurred in manufacturing semiconductor devices. For example, apparatus of embodiments of the present invention may reduce equipment expenses and promote clean room efficiency by using only one transfer chamber.

The multi-functional chamber **11** connected to the oxygen radical or plasma unit **13** annealing such as the ozone generator or the plasma generator will be described in detail with reference to Figures 7 and 8. Although Figures 7 shows a multi-functional chamber capable of

performing ozone annealing and Figure 8 shows a multi-functional chamber capable of performing plasma annealing, it is to be understood that multi-functional chambers of embodiments of the present invention may be capable of performing both ozone annealing and plasma annealing.

Turning now to Figure 7, embodiments of the multi-functional chamber connected to an annealing unit of Figure 6 having an ozone generator as the oxygen radical annealing unit will now be described. The multi-functional chamber **11** has a supporting plate **28** that holds a semiconductor wafer **27** (a semiconductor substrate). The semiconductor wafer **27** is loaded into the multi-functional chamber through an entrance **24**. A heater **29** for controlling the temperature of the semiconductor wafer between 300 and 700°C is positioned under the support plate in the lower portion of the multi-functional chamber **11**. The heater **29** preferably has the form of a lamp which can rapidly increase and decrease the temperature when the deposition temperature of the high dielectric layer is different from the oxygen radical or plasma annealing temperature of the lower electrode and/or the oxygen radical or plasma annealing temperature of the high dielectric layer. A source dispersion device **25** is positioned above the supporting plate **28**. The source dispersion device **25**, preferably a shower head, is in fluid communication with a source supplier **18**, which supplies source gas for forming a dielectric layer.

As shown in Figure 7, the source supplier **18** includes an organic source **17**, a flow controller **19**, an evaporator **21**, and a transfer gas source **23**. The organic source **17** supplies an organic source solution. As will be understood by those skilled in the art, the organic source solution may include various dielectric sources such as Ba(tetra methyl heptadionate [THD])<sub>2</sub> solution, Sr(THD)<sub>2</sub> solution, and Ti(THD)<sub>2</sub>(O-i-C<sub>3</sub>H<sub>7</sub>)<sub>2</sub> solution. Various solvents may be used to dissolve the organic source including, but not limited to, tetra hydro furan (THF), n-butyl acetate, acetone, and alcohol. In the present embodiment, a BST layer is used as

the high dielectric layer. However, when a  $Ta_2O_5$  layer is used as the high dielectric layer,  $Ta(O-C_2H_5)_5$  may be used as the source.

As illustrated in Figure 7, the organic source **17** is in fluid communication with a flow controller **19**, which is preferably a liquid mass flow controller (LMFC). The flow controller **19** is in fluid communication with an evaporator **21**, which evaporates the liquid organic source. A transfer gas source **23** is in fluid communication with the evaporator **21**. The transfer gas source **23** supplies transfer gas such as Ar gas, which mixes with the evaporated source to form evaporated source gas and transfers the organic source from the evaporator **21** to the source dispersion device **25**. While the apparatus illustrated in Figure 7 shows one evaporator **21**, it is to be understood that one, two, or three evaporators may be used. The source dispersion device **25** disperses the evaporated source gas into the multi-functional chamber **11**. Preferably, the evaporated source gas is dispersed uniformly. An oxidation gas source **22** configured to supply oxidation gas that reacts with the evaporated source gas to form the high dielectric layer is connected to the multi-functional chamber **11**.

An ozone generator **15**, which is used as the oxygen radical annealing unit, is connected to the multi-functional chamber **11** for performing an ozone annealing process in an atmosphere containing oxygen radical. The ozone generator **15** generates ozone using a gas mixture of oxygen and nitrogen as input gas. The flow rate of input gas is preferably between 1,000 sccm (standard cubic centimeter per minute) and 10 slm (standard liter per minute). The input gas preferably has a nitrogen concentration between 1 and 30%. The ozone density of the resulting ozone gas is preferably between 0.1 and 10 vol%. The ozone annealing process is performed by flowing generated ozone into the multi-functional chamber **11**. Used ozone gas is removed through an ozone remover **31**, a pump **33**, and a gas scrubber **35** installed in the exhaust end of the multi-functional chamber **11** and is finally exhausted to the outside. The pump

**33** preferably controls the pressure of the multi-functional chamber **11** in a range between 0.1 and 10 Torr.

An ultraviolet ray (UV) lamp (not shown) can be additionally installed above the semiconductor wafer, for example, in the lower end of the shower head. The UV rays may improve the efficiency of the ozone annealing process. A cleaning gas source **37** configured to supply cleaning gas such as  $\text{ClF}_3$  for cleaning the external wall of the multi-functional chamber **11** is connected to the multi-functional chamber **11**.

Referring now to Figure 8, a multi-functional chamber connected to a plasma generator will now be described. The multi-functional chamber **11** is capable of forming a dielectric layer as described above with respect to Figure 7, but utilizes a plasma generator rather than an ozone generator as an annealing unit.

As illustrated in Figure 8, the plasma generator **42** includes a wave guide **43**, magnet coils **45**, and a plasma gas source **47**.  $\text{O}_2$ ,  $\text{NH}_3$ , Ar,  $\text{N}_2$ , or  $\text{N}_2\text{O}$  gas flows from the plasma gas source **47**, and plasma of  $\text{O}_2$ ,  $\text{NH}_3$ , Ar,  $\text{N}_2$ , or  $\text{N}_2\text{O}$  is generated between the magnetic coils **45**. Generated plasma enters the multi-functional chamber **11**. The plasma generator **42** preferably generates ECR plasma using a microwave of 2.54 Ghz.

However, the plasma generator may generate RF (Radio Frequency) plasma of 13.56 MHZ.

Referring now to Figure 9, embodiments of an apparatus for forming a thin film according to embodiments of the present invention similar to the embodiments of Figure 6 and having an electrode deposition chamber will now be described. The apparatus has an electrode deposition chamber **51** connected to the transfer chamber **9**. The electrode deposition chamber **51** may be used to form a lower electrode on the semiconductor substrate and to form an upper electrode on the dielectric layer. Thus, according to embodiments of the present invention, the upper electrode can be deposited in-situ without exposing the semiconductor wafer to air after oxygen radical or plasma annealing the high dielectric layer. The

apparatus may be used to perform processes of from forming the lower electrode to oxygen radical annealing the upper electrode in-situ. The electrode deposition chamber will be described more fully with reference to Figure 10.

5           Figure 10 is a schematic diagram illustrating embodiments of the electrode deposition chamber **51** shown in Figure 9. The electrode deposition chamber **51** has a supporting plate **64** that holds a semiconductor wafer **65** (a semiconductor substrate). The semiconductor wafer **65** is loaded into the electrode deposition chamber through an  
10           entrance **63**. A heater **67** for controlling the temperature of the semiconductor wafer between 300 and 600°C is positioned under the support plate in the lower portion of the electrode deposition chamber **51**. A source dispersion device **61** is positioned above the supporting plate **64**. The source dispersion device **61**, preferably a shower head, is in fluid  
15           communication with a source supplier **54**, which supplies source gas for forming an electrode.

          As shown in Figure 10, the source supplier **54** includes an organic source **53**, a flow controller **55**, an evaporator **57**, and a transfer gas source **59**. The organic source **53** supplies an organic source solution. As  
20           will be understood by those skilled in the art, the organic source solution may include various electrode sources such as bis(ethylcyclopentadienyl) ruthenium [Ru(EtCp)<sub>2</sub>] and Ru(THD)<sub>3</sub> solutions. Various solvents may be used to dissolve the organic source including, but not limited to, tetra hydro furan (THF), n-butyl acetate, acetone, and alcohol. In the present  
25           embodiment, an Ru layer is used for forming the electrode. However, a layer formed of a Pt group metal, oxide of the Pt group layer, a metal nitride, and a heat-resistant metal can be deposited in the electrode deposition chamber according to embodiments of the present invention.

          As illustrated in Figure 10, the organic source **53** is in fluid  
30           communication with a flow controller **55**, which is preferably a liquid mass flow controller (LMFC). The flow controller **55** is in fluid communication

with an evaporator **57**, which evaporates the liquid organic source. A transfer gas source **59** is in fluid communication with the evaporator **57**. The transfer gas source **59** supplies transfer gas such as Ar gas, which mixes with the evaporated source to form evaporated source gas and transfers the organic source from the evaporator **59** to the source dispersion device **61**. While the apparatus illustrated in Figure 10 shows one evaporator **57**, it is to be understood that one, two, or three evaporators may be used. The source dispersion device **61** disperses the evaporated source gas into the electrode deposition chamber **51**. Preferably, the evaporated source gas is dispersed uniformly. The electrode deposition chamber **51** includes a pump for controlling the pressure of the electrode deposition chamber **51** between 0.1 and 10 Torr. A cleaning gas source **70** is connected to the electrode deposition chamber **51** configured to supply cleaning gas, for example,  $\text{ClF}_3$  gas which can remove source material deposited on the wall of the electrode deposition chamber **51**.

Referring now to Figure 11, an apparatus for forming a thin film according to embodiments of the present invention similar to the embodiments of Figure 9 and having a crystallization annealing chamber will now be described. A crystallization annealing chamber **71** for annealing and crystallizing the dielectric layer deposited in an amorphous state at the temperature equal to or more than the crystallization temperature is connected to the transfer chamber **9**. The crystallization annealing chamber **71** is preferably a rapid thermal annealing furnace in which the temperature rapidly rises and falls or a general hot wall single wafer type of furnace. The crystallization annealing chamber **71** controls the temperature of the semiconductor substrate between 300 and 900°C, the pressure between 0.1 and 760 Torr, and an atmosphere to be an oxidative atmosphere or a non-oxidative atmosphere. According to embodiments of the present invention, it is possible to perform crystallization annealing in-situ before or after depositing the upper



electrode, which may reduce the level of impurities and the leakage current as described above.

Turning now to Figure 12, embodiments of an apparatus for forming a thin film according to embodiments of the present invention having an electrode deposition chamber and a dielectric layer deposition chamber in fluid communication with an oxygen radical or plasma annealing unit will now be described. A dielectric deposition chamber **73** is connected to the transfer chamber **9** and is in fluid communication with the oxygen radical or plasma annealing unit **13**. The dielectric deposition chamber **73** has a structure similar to that of the multi-functional chamber **11** described above, and may be used for depositing a high dielectric layer, oxygen radical or plasma annealing a high dielectric layer, and/or oxygen radical annealing an upper electrode. Accordingly, it is possible to deposit the upper electrode in-situ without exposing the semiconductor wafer to the air after oxygen radical or plasma annealing the high dielectric layer and to perform processes of from forming the lower electrode to oxygen radical annealing the upper electrode in-situ.

Figures 13, 14 and 16 illustrate embodiments that are similar to the embodiments illustrated in Figure 12 and further include additional chambers. In Figure 13, the embodiments further include a crystallization annealing chamber **71** connected to the transfer chamber **9**. The crystallization annealing chamber **71** is similar to the crystallization chamber described above with reference to Figure 11, but controls temperature of the substrate between 400 and 900°C. The embodiments of Figure 14 include an oxygen radical or plasma annealing chamber configured to pre-treat a lower electrode **77** connected to the transfer chamber **9**. In Figure 16, the embodiments further include a crystallization annealing chamber **71** as described above with reference to Figure 11 and a cooling chamber **79**, each connected to the transfer chamber **9**. The cooling chamber **79** cools the semiconductor wafer **1** after processing before the semiconductor wafer enters the cassette **3**. A pre-heating

chamber as described below with reference to Figure 20 may also be included.

Referring now to Figure 15, embodiments of an apparatus for forming a thin film according to embodiments of the present invention having a dielectric layer deposition chamber, an electrode deposition chamber, and a crystallization annealing chamber connected to an oxygen radical or plasma annealing unit will now be described. The embodiments illustrated in Figure 15 are similar to those shown in Figure 13, except the oxygen radical or plasma annealing unit **13** is connected to the crystallization chamber **71** and not connected to the dielectric layer deposition chamber **73**. Thus, the embodiments of Figure 15 may be capable of oxygen radical annealing the upper electrode and performing crystallization annealing in one chamber, and may deposit the upper electrode in-situ without exposing the semiconductor wafer **1** to the air. Also, it may be possible to perform processes of from forming the lower electrode to oxygen radical annealing the upper electrode in-situ.

Referring now to Figure 17, embodiments of an apparatus for forming a thin film according to embodiments of the present invention similar to the embodiments of Figure 15 except having an oxygen radical or plasma annealing chamber configured to post-treat a dielectric layer in place of the crystallization annealing chamber in fluid communication with the oxygen radical or plasma annealing unit. The transfer chamber **9** is connected to the oxygen radical or plasma annealing chamber configured to post-treat a dielectric layer **81**, which is connected to the oxygen radical or plasma annealing unit **13**. The oxygen radical or plasma annealing chamber configured to post-treat a dielectric layer **81** can also be configured to post-treat, preferably by ozone annealing, an upper electrode. Therefore, using the embodiments illustrated in Figure 17, it is possible to deposit and oxygen radical or plasma anneal the high dielectric layer in-situ and to perform processes of from forming the lower electrode

to forming the upper electrode in-situ, which may reduce the leakage current of the capacitor.

Figures 18 through 20 illustrate embodiments similar to those shown in Figure 17 and having additional chambers. In Figure 18, the  
5       embodiments further include an oxygen radical or plasma anneal chamber configured to pre-treat a lower electrode **77** connected to the transfer chamber **9** and configured to oxygen radical or plasma anneal the lower electrode after forming the lower electrode. The embodiments illustrated in Figure 19 further include a crystallization annealing chamber **71** as  
10       described above with reference to Figure 11. In Figure 20, the embodiments further include a crystallization annealing chamber **71**, an electrode pretreatment chamber **77**, a pre-heating chamber **83**, and a cooling chamber **79**. The pre-heating chamber **83** raises the temperature of the substrate to around the temperature at which the dielectric layer is  
15       deposited before depositing the dielectric layer. Pre-heating the substrate may reduce the time required for stabilizing the temperature of the substrate.

In Figures 21 through 29, methods for manufacturing capacitors on substrates using the apparatus described hereinabove will now be  
20       described. In the following embodiments, reference character **a** denotes processes which can be performed in one chamber of the apparatus for forming the thin film according to embodiments of the present invention and reference character **b** denotes processes which can be performed in-situ by the apparatus for forming the thin film according to embodiments of  
25       the present invention.

Referring now to Figure 21, embodiments of a method for manufacturing a capacitor on a semiconductor substrate according to the present invention where the steps of oxygen radical or plasma annealing a lower electrode, depositing a dielectric layer, and oxygen radical or plasma  
30       annealing the dielectric layer are performed in one chamber, and where the aforementioned steps and the step of depositing an upper electrode

are performed in-situ will now be described. The lower electrode of the capacitor is formed on the semiconductor substrate (the semiconductor wafer) **101**. The lower electrode is preferably formed to a thickness of between 50 and 10,000 Å. A Pt group metal, an oxide of the Pt group metal such as RuO<sub>2</sub>, IrO<sub>2</sub>, BaRuO<sub>3</sub>, and SrRuO<sub>3</sub>, a metal nitride, or a heat-resistant metal are preferably used as the lower electrode. The lower electrode is preferably formed of the Pt group metal such as Pt, Ru, and Ir by a sputtering method, a metal organic chemical vapor deposition (MOCVD) method, or an electroplating method.

The semiconductor substrate having a lower electrode formed thereon is moved into an apparatus of embodiments of the present invention. An operation of oxygen radical or plasma annealing the lower electrode **103** is preferably performed by positioning the semiconductor substrate on which the lower electrode is formed into a multi-functional chamber containing an atmosphere comprising oxygen radical (e.g., ozone) or plasma. When the lower electrode is oxygen radical annealed by ozone annealing, the lower electrode is preferably oxygen radical annealed in the ozone atmosphere for 5 minutes under conditions where the temperature of the substrate is between room temperature and 700°C, and more preferably between 300 and 450°C, and where the density of ozone is between 0.1 and 10 vol%. Oxygen radical annealing the lower electrode by ozone annealing may further include the operation of irradiating the lower electrode with ultraviolet (UV) rays. When the lower electrode is plasma annealed, the lower electrode is preferably plasma annealed in an ECR or RF plasma atmosphere of N<sub>2</sub>O, O<sub>2</sub>, NH<sub>3</sub>, Ar, or N<sub>2</sub> under conditions where the temperature of the substrate is between room temperature and 500°C and the pressure of the chamber in which the plasma annealing is performed is between 0.1 and 10 Torr. Most preferably, the lower electrode is plasma annealed for between 1 and 10 minutes using ECR plasma of N<sub>2</sub>O gas under the condition where the temperature of the substrate is 200°C.

An operation of depositing a dielectric layer **105** on the lower electrode is preferably performed by a chemical vapor deposition method or by a physical vapor deposition method such as sputtering in the multi-functional chamber. More preferably, a high dielectric layer, such as a BST layer, is deposited. The dielectric layer is preferably deposited to a thickness of between 100 and 500 Å. Most preferably, a BST layer is deposited on the lower electrode by the MOCVD method using an organic source containing Ba(THD)<sub>2</sub>, Sr(THD)<sub>2</sub>, and Ti(THD)<sub>2</sub> and an oxidation gas that is a mixed gas of O<sub>2</sub> and N<sub>2</sub>O under the conditions where the temperature of the substrate is between 400 and 600°C and the pressure of the chamber is between 1 and 10 Torr.

An operation of oxygen radical or plasma annealing the dielectric layer **107** is performed in the multi-functional chamber. The dielectric layer is oxygen radical or plasma annealed in an atmosphere containing oxygen radical or plasma gas, as described above for oxygen radical or plasma annealing the lower electrode. In order to improve the effect of oxygen radical or plasma annealing the dielectric layer, the processes of depositing and oxygen radical or plasma annealing the dielectric layer can be repeated "n" times. The thickness of the high dielectric layer deposited in one cycle is preferably between 20 and 200 Å.

The oxygen radical or plasma annealed semiconductor substrate is transferred to an electrode deposition chamber. An upper electrode is deposited **109** on the oxygen radical or plasma annealed dielectric layer. The upper electrode preferably has a thickness of between 50 and 3,000 Å. The upper electrode is preferably formed using a material the same as the material of which the lower electrode is formed by a physical deposition method, such as sputtering, or by a MOCVD method. For example, the Ru layer is deposited by the MOCVD method using Ru(EtCp)<sub>2</sub> as a source under the conditions where the temperature of the substrate is between 150 and 500°C and the pressure of the electrode deposition chamber is between 0.1 and 10 Torr.

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The semiconductor substrate on which the upper electrode is deposited is moved out of the apparatus to a crystallization annealing chamber and is crystallization annealed **111**. Preferably, the BST layer is crystallization annealed at the temperature between 500 and 800°C in an oxidative or non-oxidative atmosphere under the condition where the pressure of the chamber is between 0.1 and 10 Torr. When Ru is used as the electrode of the capacitor having a BST layer, Ru containing oxygen is oxidized. Crystallization annealing is preferably performed in an atmosphere where a small amount of oxygen is contained or in a non-oxidative atmosphere. When Pt is used as the electrode of the capacitor having a BST layer, crystallization annealing is preferably performed using a mixed gas of O<sub>2</sub> and N<sub>2</sub> containing between 1 and 10 % oxygen. Crystallization annealing is preferably performed for between 30 seconds and 30 minutes at the annealing temperature of 750°C. It may take longer to perform crystallization annealing for a capacitor having a Pt electrode than for a capacitor having a Ru electrode when the temperature at which annealing is performed is lower. A rapid thermal annealing (RTA) process is preferably used in order to reduce the degree to which annealing during the formation of the capacitor affects the characteristics of other devices. In other embodiments illustrated in Figure 22, the operation of performing crystallization annealing is performed in situ, while in still other embodiments shown in Figure 23, crystallization annealing is not performed. In the embodiments of Figure 27, the operations of forming a lower electrode and performing crystallization annealing are performed in situ.

The embodiments illustrate in Figure 24 are similar to those described above with reference to Figure 21, except the oxygen radical or plasma annealing of the lower electrode **103** and the depositing of the dielectric layer **105** are performed in separate chambers of the apparatus and the operations of oxygen radical or plasma annealing the dielectric layer **107** and performing crystallization annealing **111** are performed in a

single chamber, with the crystallization annealing operation **111** being performed before depositing the upper electrode **109**. Figure 25 shows embodiments similar to those of Figure 24 except the lower electrode is not oxygen radical or plasma annealed.

5           The embodiments illustrated in Figure 26 are similar to those illustrated in Figure 22 except the lower electrode is not oxygen radical or plasma annealed and operations of pre-heating the substrate **113** before depositing the dielectric layer **105** and cooling the substrate **115** after crystallization annealing **111** are performed. The pre-heating operation  
10           preferably raises the temperature of the substrate to the process temperature of the next step. The pre-heating operation is preferably performed within 5 minutes. The cooling operations preferably cools the substrate to room temperature within 5 minutes. The processes of from pre-heating the substrate to cooling the substrate are performed in-situ and  
15           the processes of depositing the dielectric layer and oxygen radical or plasma annealing the dielectric layer are performed in one chamber.

          The embodiments illustrated in Figure 28 are similar to those illustrated in Figure 23 except the lower electrode is not oxygen radical or plasma annealed and an operation of oxygen radical annealing the upper  
20           electrode **117** is performed. The upper electrode is oxygen radical annealed in the multi-functional chamber. The upper electrode is preferably oxygen radical annealed in an atmosphere containing oxygen radical (e.g., ozone) for between about 30 seconds and 30 minutes under conditions where the temperature of the substrate is between 200 and  
25           600°C and the density of ozone is between 0.1 and 10 vol%. The oxygen radical annealing of the upper electrode may include irradiating the substrate with UV rays, which may also aid in reducing the leakage current of the capacitor.

          The embodiments of Figure 29 are similar to those illustrated in  
30           Figure 28 except the operation of depositing the upper electrode is performed using multiple steps. A first upper electrode is deposited **119** as

described above with reference to Figure 28. The first upper electrode is preferably formed to a thickness of between 50 and 1,000 Å so that oxygen radicals may pass through the first upper electrode. Then, the first upper electrode is oxygen radical annealed **121** under the same conditions described above with reference to Figure 28. A second upper electrode is then deposited **123** on the oxygen radical annealed first upper electrode. The second electrode preferably has a thickness of between 50 and 3,000 Å. Depositing the upper electrode in multiple steps with intervening oxygen radical annealing steps may aid in reducing the leakage current of the capacitor while increasing the thickness of the entire upper electrode.

Referring now to Figure 30, a lateral cross-section of a capacitor formed on a semiconductor substrate using the embodiments of Figure 28 will now be described. A transistor having a source region **105**, a drain region **107**, and a gate electrode **111** which interposes a gate oxide layer **109** is formed in the active region of a semiconductor substrate **101** restricted by a field insulating layer **103**. A bit line **113** is formed on the drain region **107**. A lower electrode **121** connected to the source region **105** through a plug **117** and a barrier metal layer **119** formed in a contact hole in an interlayer dielectric layer **115** is formed in the source region **105**. The lower electrode **121** is preferably formed of the Pt group metal, the oxide of the Pt group metal, the metal nitride, or the heat-resistant metal to a thickness between 50 and 10,000 Å by the sputtering method, the MOCVD method, or the electroplating method.

As shown in Figure 30, a dielectric layer **123** and an upper electrode **125** are formed on the lower electrode **121**. The dielectric layer **123** is preferably formed as a high dielectric layer containing materials such as BST, Ta<sub>2</sub>O<sub>5</sub>, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, Y<sub>2</sub>O<sub>3</sub>, SrTiO<sub>3</sub> (STO), PbZrTiO<sub>3</sub> (PZT), SrBi<sub>2</sub>Ta<sub>2</sub>O<sub>9</sub> (SBT), PbZrO<sub>3</sub>, LaZrO<sub>3</sub>, PbTiO<sub>3</sub>, LaTiO<sub>3</sub>, and Bi<sub>4</sub>Ti<sub>3</sub>O<sub>12</sub>, as described above. The upper electrode **125** is preferably formed of the same material as the material of which the lower electrode **121** is formed by the same method as the method by which the lower electrode **121** is formed.



The leakage current of the capacitor may be reduced by oxygen radical annealing the entire surface of the upper electrode in an atmosphere containing oxygen radical (e.g., ozone) **127**. As described above with reference to Figure 29, the thickness of the upper electrode may then be increased by forming a second upper electrode on the oxygen radical annealed upper electrode **125**.

According to embodiments of the present invention, it is possible to reduce the leakage current by oxygen radical or plasma annealing the lower electrode after forming the lower electrode and/or oxygen radical or plasma annealing the dielectric layer after forming the dielectric layer. The reduction in leakage current may be due to a reduction in the level of impurities in or on the various layers of the capacitor. Oxygen radical (e.g., ozone) annealing the upper electrode after forming the upper electrode has been found to reduce the leakage current of the capacitor, which reduction may be caused by a decrease in the number of oxygen vacancies in the high dielectric layer. The apparatus for forming a thin film of embodiments of the present invention may reduce or prevent absorption of impurities on the lower electrode or the high dielectric electrode by reducing the exposure of the substrate to air during the processing steps. Accordingly, the apparatus of embodiments of the present invention may reduce the leakage current of the capacitor.

In the drawings and specification, there have been disclosed typical preferred embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.